

COUNTER CURRENT MIXING REACTOR

Field of the Invention

The invention is a counter current mixing reactor enabling the efficient
5 mixing of streams of fluid. More specifically, one stream may be of a
heated, pressurised or supercritical fluid whilst another is of a denser
fluid. More preferably, one stream may be of supercritical water (scH_2O),
and another is of a metal containing solution. Most preferably, the
invention can be used in the continuous synthesis of nanoparticles of
10 metals or metal oxides in high temperature water without blockage of
pipeworks and with improved control of particle size and shape compared
to previous designs of reactor.

Background of the Invention

15 Metal and metal oxide particles with nanometer scale dimensions have a
wide range of uses, including (but not limited to) catalysts, pigments,
polishes, ultraviolet absorbers and in ceramics. It is well known that such
particles can be formed by chemical reaction of aqueous solutions of metal
salts with heated, pressurised or supercritical water. In principle, this
20 methodology offers distinct advantages over other methods of nanoparticle
creation in terms of cost and viability as it allows the reaction to be
performed as a continuous process. However it is difficult to perform this
reaction on a commercial scale utilising current methods because existing
reactor configurations do not allow the precipitation reaction to be
25 controlled effectively leading to frequent blockage of the reactor and
inadequate control of particle size and shape. Hence within this process,
the design of the reactor where the water and the salt solution mix is of
crucial importance to the size and properties of the nanoparticles
produced.

The invention details a more efficient and versatile method of producing a range of nanoparticles of metal and metal oxides that could be catalytically active, and thus clearly possesses industrial applicability.

5 Particle size can be important for catalytic processes and other uses, and is dependant on the nature of the metal and also the intended application. For example commercially useful cerium oxide (from Johnson Matthey) has a surface area of 250m²/g whereas silver particulate with a lower surface area, 60-100m²/g, is also commercially useful. Without
10 optimisation, the reactor of the invention has produced particulates of CeO₂ with surface areas of 100m²/g. This could, in principle, be improved considerably with additional work focussed on lowering the particle sizes produced by adjusting the operating conditions and metal salt concentrations.

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Whilst the surface area of a catalyst is very important, the physical nature of the particles can also determine their success in the intended application. For example, zirconium oxide nanoparticulates are often amorphous in structure, which is not an appropriate form for many
20 catalytic applications. The reactor of the invention has prepared crystalline ZrO₂, which is much more useful.

Supercritical fluids, and particularly supercritical water, have been used to produce metal nanoparticles (Adschiri, Kanazawa et al. 1992; Adschiri, Hakuta et al. 2000; Galkin, Kostyuk et al. 2000; Adschiri, Hakuta et al.
25 2001; Cabanas, Darr et al. 2001; Cote, Teja et al. 2002; Hao and Teja 2003; Viswanathan and Gupta 2003; Viswanathan, Lilly et al. 2003) however the existing methodologies all use variants on either a T- or a Y-shaped reactor (Figure 1).

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A major limitation of these methods is that the location of the precipitation of the particles is not controlled. Particles are known to precipitate readily in reactor pipework, especially inlet pipes. The T piece reactors have been found to block frequently at the denser fluid inlet, resulting in costly and inconvenient down time being required for reactor cleaning and reassembly. These blockages can occur within minutes of the denser fluid feed reaching the T piece. Additionally, if the system is under pressure there are obvious health and safety implications associated with frequent blockages (i.e. increased risk of explosion). The invention consists of a novel design of reactor that largely eliminates these problems.

Statement of Invention

Thus, according to a first aspect of the invention there is provided a counter current mixing reactor for continuously mixing two or more fluids of differing densities comprising a first inlet and an outlet characterised in that one or more further inlets are diametrically opposed to the first inlet and are disposed within the outlet.

The principle advantage of the invention is that the mixing reactor exploits the differences in density between the fluids to avoid premixing or stagnation thus minimising blockage of the pipework or reactor. This is the main problem with other reactor configurations and is caused by back mixing in the inlets to the mixer. This causes particulate formation upstream of the mixing point and consequent flow restriction and eventual blockage of the reactor. The invention eliminates this by removing the potential for mixing to occur in the inlets of the reactor.

It will be appreciated that references to 'differing densities' include differences in the order of greater than 5%, 10%, 20%, 50%, 100%, 500% or ranges between any of these values.

In one embodiment of the invention, there is provided a counter current mixing reactor for continuously mixing two fluids comprising a first inlet and an outlet characterised in that a further inlet is diametrically opposed
5 to the first inlet and is disposed within the outlet.

Preferably, the one or more further inlets are co-axially disposed within the outlet.

10 In a further embodiment of the invention, there is provided a first conduit adapted to contain a reaction fluid flowing in a first direction, and an outlet of a second conduit adapted to contain a second reaction fluid, said outlet having at least a component of which facing in a direction generally opposite to said first direction, and said outlet being disposed in said first
15 conduit.

It will be appreciated that references to 'generally opposite' refer to angles ranging from sideways (45°) to diametrically opposed (180°).

20 In a yet further embodiment of the invention, the counter current mixing reactor is arranged in a vertical configuration. In such a configuration the fluid of lower density may be introduced into the upper inlet and thus may be mixed with a fluid of higher density introduced into the lower inlet.

25 Preferably, at least one of the fluids is in the sub, near critical or supercritical state. It will be appreciated that references to supercritical fluid include hydrocarbons (e.g. acetone), water or a dense phase gas. More preferably, at least one of the fluids e.g. the fluid of lower density, is heated, pressurised or supercritical water.

Preferably, the fluid of lower density e.g. heated, pressurised or supercritical water, is kept hot using a heater around the outlet. This is advantageous because it allows the reactions to continue beyond the initial mixing point, thereby improving the quality or quantity of the product particles.

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Preferably, at least one of the fluids is a solution of a metal salt or compound, more preferably an aqueous solution of a metal salt or compound, most preferably, a transition metal salt solution. Particularly preferably, at least one of the fluids e.g. the fluid of higher density, is an aqueous metal salt solution of the metals selected from transition metals including ruthenium, cadmium, rhodium, palladium, iron, cerium, titanium, zirconium, copper and silver, especially preferably, the metal salt is an oxide.

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The fluid of higher density is preferably cooler than the fluid of lower density. To achieve this, the fluid of higher density is cooled prior to introduction to the mixing reactor and/or the fluid of lower density is warmed prior to introduction to the mixing reactor.

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The advantage of cooling the fluid of higher density e.g. the metal salt solution, is that it allows the metal salt to remain relatively cool until mixing occurs. Thus, no preheating of the metal salt solution occurs. This both saves on energy and removes the possibility that increasing the temperature of the salt stream will cause the metal salt to precipitate prematurely. This is known to happen for certain metal salts e.g. copper salts can precipitate out of solution if the bulk temperature of the metal salt solution is over 50-60°C. The tendency for premature precipitation depends partly on the metal salt and also its concentration in solution. Furthermore, the rapid heating of the metal salt solution on contact with the much hotter supercritical H₂O stream instantaneously causes particles to form. Additionally, the invention eliminates the problems of blockage

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experienced with previous reactor designs by keeping the aqueous salt stream cold and preventing mixing or interaction of this aqueous stream until it reaches the region in which the chemical reaction occurs. This surprisingly controls the precipitation and localises it at the point of the chemical reaction. An additional benefit is that the cold salt solution can also act as effective heat sink, removing the heat from an exothermic reaction.

Preferably, the fluid of higher density e.g. metal salt solution, is cooled using a heat sink. The advantage of using a heat sink around the metal salt inlet is to ensure efficient heat dissipation away from the reaction – this is not practical with most existing reactor designs which cannot be cooled without hindering the mixing of the two streams.

It will be appreciated that regardless of whether the fluid of higher density is cooled or the fluid of lower density is heated, there is preferably a temperature differential between the two fluid streams. Ideally, such a temperature differential will be in the order of greater than 50, 100, 200, 300, 400 or 500°C or ranges between any of these values. Most preferably, the temperature differential is 380°C.

In a further embodiment of the invention, the one or more further inlets comprise a shaped nozzle, for example, a conical funnel.

The funnel configuration allows a controlled and symmetrical mixing of the two streams. This is a marked contrast to the current state of the art, where a T-piece is commonly used to mix the two streams. It should be noted that the funnel is not an essential part of the design, since the reactor can be run with only a pipe. However, the funnel aids the mixing of the two solutions and allows more consistent particle size and morphology to be obtained than if the inlet is only a pipe. The T-piece

favoured in the prior art did not create uniform mixing across the inlets into the mixing zone, resulting in frequent reactor blockage and consequent down time.

- 5 Preferably, the two or more fluid streams are mixed under pressure. More preferably, the two or more fluid streams are pressurised to the order of 50, 100, 200, 300 or 400 bar or ranges between any of these values. Most preferably, the two or more fluid streams are pressurised to 225 bar.
- 10 As a second aspect of the invention there is provided a mixing chamber comprising one or more mixing reactors of the invention arranged in series. This arrangement has the advantage of allowing consecutive mixing of two or more fluids for further refinement of particle size.
- 15 As a third aspect of the invention, there is provided a process for preparing metal nanoparticles which comprises delivery of a metal salt solution through a first inlet of a mixing reactor according to the invention and delivery of a fluid in the sub, near critical or supercritical state (e.g. supercritical water) through a further inlet diametrically
- 20 opposed to the first inlet wherein said further inlet is disposed within an outlet such that the mixed solutions exit the reactor once mixed.

The more efficient mixing provided by the invention allows the production of metal oxide nanoparticles with surface areas significantly higher than previously

25 observed. For example, ZrO_2 nanoparticles have been produced by the process of the invention with a relatively high surface area of $200\text{m}^2/\text{g}$ which could potentially increase their catalytic activity. Metal and metal oxides that have been previously difficult to produce have been prepared in the reactor of the invention with significantly reduced blocking, e.g. silver, at around $60\text{m}^2/\text{g}$. This

30 demonstrates that a broader range of potential nanoparticulates metal based

catalysts could be produced in the mixing reactor of the invention than in existing designs of equipment.

5 As a fourth aspect of the invention, there is provided a process for preparing metal nanoparticles which comprises mixing a solution of supercritical water with an aqueous metal (e.g. transition metal) salt solution, characterised in that the aqueous metal salt solution is cooled prior to mixing.

10 As a fifth aspect of the invention, there is provided metal nanoparticles obtainable by a process as defined herein. Preferably, the particles obtained are a mixture of two or more metals.

Brief Description of the Drawings

15 Figure 1: Schematic representation of commonly known T- and Y-shaped reactors.

Figure 2: Schematic representation of the counter current mixing reactor of the invention.

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Figure 3: Schematic representation of the funnel arrangement within the counter current mixing reactor of the invention generated by CFD modelling.

25 Figure 4: Schematic representation of a rig which incorporates the counter current mixing reactor of the invention allowing continuous production of particles.

30 Figure 5: Graph demonstrating the effect of increasing flow rate upon the surface area of resultant particles.

Figure 6: Graph demonstrating the effect of increasing temperature upon the surface area of resultant particles.

Description of the Invention

- 5 Referring first to Figure 2, the aqueous stream is introduced into the bottom of the reactor, where it is cooled, preferably by a heat sink. The solution is forced under pressure in an upwards direction. The supercritical water is introduced into the reactor in the opposite direction – i.e. downwards. The scH_2O is less dense than the aqueous stream, and
- 10 thus rises upwards in the reaction chamber, becoming intimately mixed with the aqueous salt solution as it does so. This mixing is highly efficient, and results in the generation of metal oxide nanoparticles that can be separated downstream from the aqueous effluent.
- 15 This design takes advantage of the density differential between the two reactant streams (i.e. the scH_2O and the cold aqueous salt solution). This differential creates a strong, desirable mixing environment within the reactor and induces strong eddies downstream of the mixing point. These eddies are desirable as they help to disperse the metal oxide particles and
- 20 carry them away such that they do not block the reactor.

In a preferred embodiment the reactor incorporates a funnel as shown in Figure 3. This aids the mixing of the reactants, and avoids a pulsing phenomenon associated with the mixing downstream. As the scH_2O is less

25 dense and is therefore more buoyant than the cold solution into which it is flowing a film of scH_2O forms on the surface of the funnel. This film mixes very efficiently with the colder aqueous solution flowing past it, and this has a beneficial effect on the kinetics of the reaction between the scH_2O and the aqueous solution.

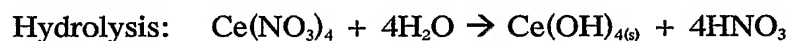
Figure 4 is a flow diagram of a rig incorporating the mixing reactor of the invention generally as 1. The rig comprises a preheater oven which heats water to a temperature of 400°C. The water stream is then pumped from a first reservoir containing water under a pressure of 225 bar to an upper inlet by a Gilson HPLC pump. Simultaneously, a stream of an aqueous metal salt is pumped from a second reservoir containing aqueous metal salt under a pressure of 225 bar through a lower inlet by an additional Gilson HPLC pump at room temperature. Following mixing, the mixed streams pass through a water cooler which functions to cool the stream before being filtered under pressure by a pressure transducer 2 regulated by a Tescom back-pressure regulator. Following filtration under pressure, nanoparticles 3 may then be collected.

The invention will now be described with reference to the following non-limiting Examples:

Example 1: The production of Nanoparticulate CeO₂

Reaction Scheme:

The following reaction was carried out using the mixing reactor of the invention incorporated into a rig configuration shown in Figure 4.



System pressure was set to 228 bar. The metal salt solution (Ce(NO₃)₄, (0.2 M)) was flowed at 5 ml/min through the reactor. A total of 250 ml of the metal salt solution was used during the course of the 50 min run. The scH₂O was flowed at 10 ml/min through the reactor at a temperature of 400 °C. The reactor was maintained at a temperature of 370 °C using a band heater for the duration of the reaction.

The high pressure pumps and back pressure regulator system allow the pressure to be maintained throughout the rig and then to be reduced at the end allowing liquid product to be released at ambient temperature and pressure. The rig, using
5 the invention can be run for hours without blocking producing 2-5g per hour of the metal oxide.

A selection of other results obtained from the mixing reactor of the invention using similar flow and concentration conditions as described above is shown in
10 Table 1 below:

Table 1

<i>Metal Type</i>	<i>BET surface area</i>	<i>Average Particle Size (either from XRD or surface area calculation)</i>
TiO ₂	113 m ² /g	13nm
CeO ₂	average 100m ² /g	9nm
ZrO ₂	194m ² /g	6nm
ZnO	16.5 m ² /g	64 nm
CuO / Cu ₂ O / Cu	10 - 20 m ² /g	50nm
Cu _{0.5} Zn _{0.5} O ₂	55m ² /g	15nm
Fe ₂ O ₃	218m ² /g	21nm
Ag	60m ² /g	9nm

Example 2: Control over surface area with flow rate within the reactor

- 5 Figure 5 shows the effect of increasing flow rate of cerium nitrate up through the reactor. Clearly there is an interesting trend of increasing surface area (from 65m²/g up to 100m²/g) with increasing metal salt flow up to a value of 8ml/min beyond which the particle size begins to decrease. It is possible that the increase is caused by the relationship between flow velocity and reaction kinetics and the
- 10 decrease is caused by an 'excess' of metal salt resulting in larger particles being produced.

Example 3: Control over surface area with temperature within the reactor

- One area of interest is the effect of the operating temperature within the reactor and it's impact on surface area. The reactor can be heated externally to any given
- 15 temperature sub, near or super critical, the relationship between surface area (and indirectly, particle size) and operating temperature can be established. Even though the heated water inlet inside the reactor may be operating sub critical, the temperature differential between the metal salt and the heated water still exists

and this will cause the inlet flow to turn upwards into the downstream outlet of the pipe, as shown in Figure 2.

Figure 6 is a graph showing how surface area increases significantly with operating temperature. This indicates that the particle size (and possibly the morphology) can be tailored by adjusting the operating conditions of the reactor.

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